МАТЕРІАЛОЗНАВСТВО

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INFLUENCE OF BINARY ALLOY OF THE AL-MN SYSTEM ON THE TRIBOLOGICAL PROPERTIES OF ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE

The article considers the effect of the percentage content of the liquid-quenched dispersed (50—100 μm) binary alloy of the Al-Mn system on the tribological properties of ultra-high-molecular-weight polyethylene under different operating conditions, such as the action of rigidly fixed abrasive particles and friction conditions without lubrication according to the "disk-pad" scheme. We discovered that introducing dispersed particles of a hard (HV ≈ 600 MPa) Al-11.6 % Mn alloy reduces the linear wear rate by 8.7 times and the abrasive wear index by 1.8 times compared to the pure polymer. The effect of microreinforcement explains the increase in wear resistance. It provides a uniform distribution of the applied load in the friction zone and decreases local stresses. Morphological analysis of the friction surfaces confirmed the formation of a more homogeneous surface layer structure. It is shown that increasing the alloy content to 25—30 wt. % leads to particle agglomeration, the formation of local stress concentrators, and deterioration of the tribological properties of polymer composites.

***Keywords**: ultra-high-molecular-weight polyethylene; liquid-quenched Al-Mn alloy; tribological properties; abrasive wear index; linear wear rate, hardness.*

Розглянуто вплив вмісту загартованого з рідкого стану дисперсного (50—100 мкм) бінарного сплаву системи Al-Mn на трибологічні властивості надвисокомолекулярного поліетилену в різних умовах експлуатації: при дії жорстко закріплених абразивних часток та за умов тертя без змащення за схемою «диск-колодка». Встановлено, що введення дисперсних часток твердого (HV ≈ 600 МПа) сплаву Al-11,6 % Mn зменшує інтенсивність лінійного зношування у 8,7 разів та показник абразивного стирання у 1,8 раза порівняно з чистим полімером. Підвищення зносостійкості пояснюється ефектом мікропідсилення, який забезпечує рівномірний розподіл прикладного навантаження в зоні тертя та зниження локальних напружень. Морфологічний аналіз поверхонь тертя підтвердив формування більш однорідної структури поверхневого шару. Показано, що збільшення вмісту сплаву до 25—30 мас.% призводить до агломерації часток, утворення локальних концентраторів напружень та погіршення трибологічних властивостей полімерних композитів.

***Ключові слова**: надвисокомолекулярний поліетилен; загартований з рідини сплав Al-Mn; трибологічні властивості; показник абразивного стирання; інтенсивність лінійного зношування; твердість.*

Problem's formulation

Wear is one of the main reasons for the loss of efficiency, and consequently, the reduction in the durability of the working parts of machines and mechanisms in the agricultural industry. It is caused by surface damage in almost 90 % of cases. Among these process varieties, adhesive and abrasive wear are the most common [1]. The first is associated with the formation and destruction of microzones of adhesion between contacting surfaces, which in turn leads to their local setting and plastic deformation. The second is mainly considered a process of mechanical surface destruction due to significant force loads and multiple impacts of solid particles, particularly stones, sand, and crop residues [2]. Therefore, an integrated approach to reducing adhesive and abrasive wear of the working parts of agricultural machinery is an essential factor in increasing the economic efficiency of the agricultural sector. Using modern polymer composite materials (PCMs) based on thermoplastic polymers containing powder fillers (FLs) is one of the most promising ways of implementing it. Using such PCMs allows reducing the number of scheduled and unscheduled preventive maintenance measures for equipment, increasing the durability and reliability of the working parts of machines and mechanisms. In addition, replacing scarce metals and alloys with PCMs makes it possible to significantly reduce the labour intensity of their manufacture through high-performance technologies, which provides significant savings in resources. Moreover, using injection moulding and compression moulding methods when manufacturing parts from PCMs, including those of complex configuration, allows for reduced labour costs and the cost of products by 6 and 9 times, respectively [3—5].

Analysis of recent research and publications

Materials based on ultra-high-molecular-weight polyethylene (UHMWPE) attract considerable attention among the known PCMs resistant to the effects of abrasive particles. This polymer is distinguished by its low weight in combination with high functional properties, among which it is worth noting resistance to the effects of many aggressive environments (in particular, 50- and 70 % solutions of hydrochloric acid, diesel fuel, acetone, white spirit), preservation of operability at cryogenic temperatures (73 K), and high water repellency, which prevents freezing and sticking of moisture-containing materials on its surface. However, specific properties limit the widespread implementation of UHMWPE. Low wear resistance under adhesive wear conditions, hardness and thermal conductivity, tendency to plastic deformation under the influence of prolonged loads, and high melt viscosity complicate its processing by injection moulding [6]. We introduced FLs of various nature and form into UHMWPE in order to improve these characteristics: nanoclay and nanodiamonds, silicon dioxide and carbide, zinc oxide, zirconium, aluminium and graphene, zeolite, Ti-Al-V alloy, carbon nanotubes, hydroxyapatite, anthracite, bauxite, aluminosilicate microspheres, and crucible graphite [6, 7]. Introducing them into UHMWPE contributes to an increase in wear resistance, hardness, tensile strength, yield strength, and elastic modulus by several orders of magnitude, which, in turn, expands the scope of practical application of such PCMs in the manufacture of parts of working bodies of machines and mechanisms of the agricultural industry [8, 9]. Considering the above, searching for new PCM compositions based on UHMWPE is an urgent task of modern scientific and practical materials science.

Formulation of the study purpose

Taking the above into account, the aim of this work is to study the effect of the percentage content of the dispersed binary alloy of the Al-Mn system on the tribotechnical characteristics of UHMWPE under various operating conditions.

Presenting main material

We used UHMWPE (manufactured by Jiujiang Zhongke Xinxing New Material Co., Ltd, China) with a molecular weight of 5—5.5 million g/mol, which is characterised by stable functional properties under the influence of aggressive environments, to create new PCMs. We selected a dispersed (50—100 μm) Al-Mn alloy as a metal filler. It was quenched from the liquid state at a rate of ~10^6 K/s and a mass fraction of Mn in the alloy of 11.6 wt. %. It is characterised by a combination of unique physical and mechanical properties due to a highly supersaturated substitutional solid solution in the quenched structure, and according to X-ray structural analysis (X-ray diffraction) of the remains of the peritectic solid phase of Al_6Mn. We performed X-ray diffraction on a DRON-2.0 diffractometer in monochromatized $Cu_{K\alpha}$ radiation. The practical absence of solubility of Mn atoms in the Al fcc lattice characterises the Al-Mn phase diagram. Quenching from the liquid state (QLS) allows significantly increase in the solubility of Mn in aluminium up to 11.6 wt. %, as evidenced by an almost linear decrease in the Al crystal lattice period (Fig. 1) of the quenched Al-Mn alloy, depending on the manganese content compared to the minimum value *a* = 0.4033 nm, determined by the line from the (420) plane. X-ray structural analysis of the QLS of Al-Mn alloys (4.8 wt. % Mn) recorded only the lines of a single-phase fcc solid substitution solution, which is explained by the complete substitution of Al atoms by Mn atoms. The sizes of the radii of aluminium and manganese atoms, respectively, 0.143 nm and 0.13 nm, clearly indicate the type of solid solution [10, 11].

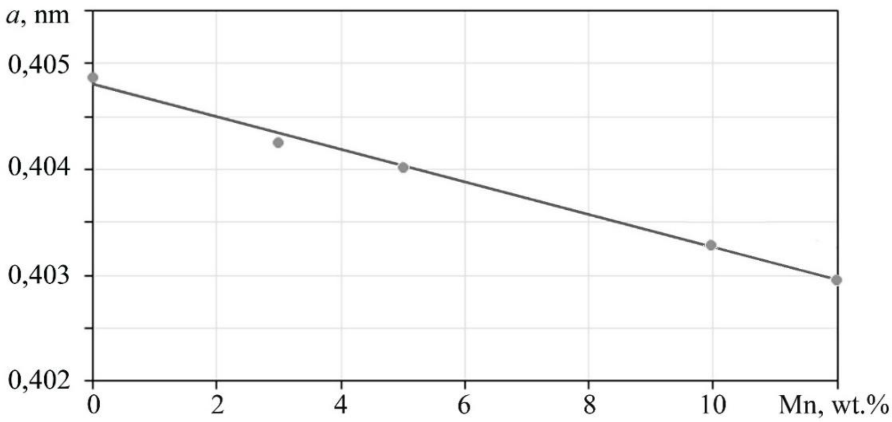


Fig. 1. Dependence of the crystal lattice period of QLS samples of Al-Mn alloy on the Mn content

The high level of mechanical characteristics of the alloy is due to a significant difference in the interatomic radii of Al and Mn. Under conditions of non-equilibrium crystallisation, this leads to the emergence of substantial microstresses in the fcc-Al lattice. Fig. 1 shows that the degree of elastic deformation of the lattice increases due to the influence of smaller Mn atoms with increased Mn content. A high level of microstresses (almost up to $\Delta a/a \sim 3{,}2\cdot10^{-3}$) confirms this. They also contribute to an increase in the wear resistance of the UHMWPE. At the same time, the QLS also leads to the crushing of the so-called coherent X-ray scattering regions, which is accompanied by a significant increase in the dislocation density to $3{,}5\cdot10^{11}$ cm^{-2}, contributing to the rise in mechanical characteristics [10]. The specified parameters of the fine structure (dislocation density and microstresses) positively affect the level of mechanical properties of materials. According to the method given in [10], we performed the calculations of the $\Delta a/a$ parameter of the QLS of the aluminium alloy Al-Mn by the formula:

$$\frac{\Delta a}{a} = \frac{\beta}{4\cdot tg\theta},$$

where β is the integral width of the diffraction line (222); θ is the reflection angle.

We performed the formation of products containing 5—30 wt.% FL according to the regime. Its method is given in [12]. Using the HECKERT experimental machine, we determined the abrasive wear index on rigidly fixed abrasive particles with a dispersion of 100 μm for UHMWPE and PCMs based on it at a fixed load of 10 N [6]. We determined the linear wear intensity of UHMWPE and PCMs under friction conditions without lubrication during rotational motion according to the “disk-pad” scheme on the SMC-2 friction machine at a sliding speed of 1 m/s and a load of 1 MPa. We used a steel (steel 45) cylinder with a diameter of 30 mm, a hardness of 45—48 HRC, and a surface roughness of R_a = 0.32 μm as a counterbody. The hardness of the UHMWPE and PCMs was determined on the Rockwell HRR scale using the 2074 TPR device. We analysed the morphology of the friction surfaces of the test specimens using a binocular microscope BIOLAM-M in reflected incident light, which allowed obtaining detailed and high-quality images. The roughness parameters after the tests were determined on the R_a scale using the 170621 probe profilometer. Using the PMT-3M microhardness tester, we measured the microhardness index of the FL at a load of 5 g and a holding time of 20 seconds.

According to the data given in Tabl. 1, we can see that introducing QLS binary Al-11.6 % Mn alloy leads to a decrease in the linear wear intensity and the abrasive wear index of the UHMWPE by 8.7 and 1.8 times, respectively. The increase in the wear resistance of the UHMWPE under different operating conditions is explained by the fact that the hard (microhardness ≈ 620 MPa, maximum strength = 590 MPa) dispersed particles of the ZRS-alloy Al-11.6 % Mn strengthen the surface layer of the polymer, increasing its hardness by 1.8 times, reducing its susceptibility to microdeformations and plastic fracture. This is confirmed by a decrease in microroughnesses (see Fig. 2) and the formation of a more uniform and dense structure of the friction surface, which correlates with a reduction in surface roughness after testing by 1.7 times.

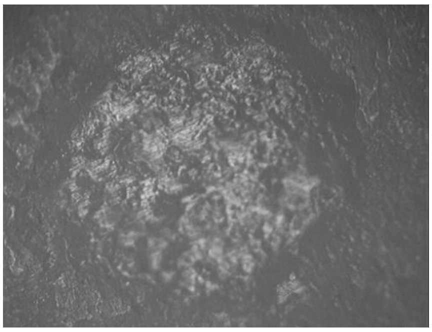
Table 1. Functional properties of UHMWPE and PCMs based on it

Index	Filler content, wt. %						
	0	5	10	15	20	25	30
Linear wear rate *, $I_h \cdot 10^{-7}$	15,8	11,1	6,2	2,6	1,8	2,4	6,5
Abrasive wear index*, V_i, mm^3/m	1,36	1,02	0,82	0,76	0,74	0,85	0,97
Hardness HRR, hardness units	32	37	41	48	57	51	47
Friction surfaces roughness ***, R_a, μm:							
- under friction conditions without lubrication	2,14	1,93	1,72	1,47	1,23	1,31	1,62
- under the influence of rigidly fixed abrasive particles	2,57	2,27	1,96	1,84	1,80	2,01	2,23

* average value of at least 3 experiments

**average value of 5 cycles of experiments

***average value of at least 12 measurements



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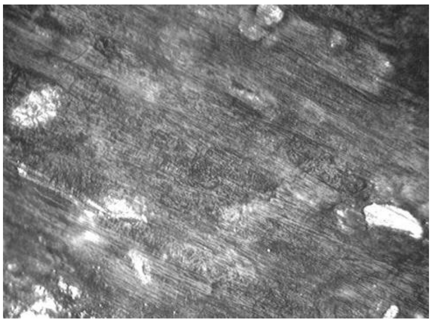

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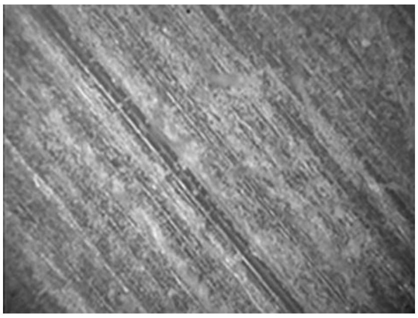

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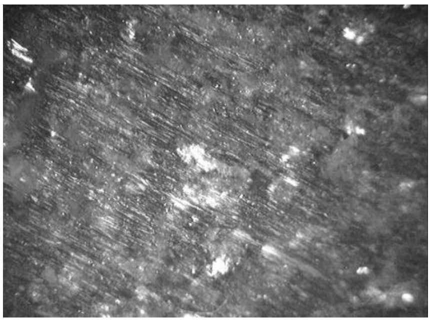

2)

b

Fig. 2. Friction surfaces (×200) of pure UHMWPE (1) and its composite (2) containing 20 wt. % Al-11.6 % Mn under friction conditions without lubrication (a) and on rigidly attached abrasive particles (b)

In addition, the presence of finely dispersed Al-Mn particles in the volume of the UHMWPE creates a micro-reinforcement effect: the applied load during contact with abrasive particles and a steel counter body is evenly distributed over the friction surface. This, in turn, reduces local stresses and temperature in the contact zone, minimising the likelihood of adhesive wear. Morphological analysis of the friction surfaces confirms the obtained data. For pure UHMWPE, traces of plastic deformation and a zone of adhesion with a steel counter body are characteristic, which indicates the predominance of the adhesive wear mechanism. In the case of PCMs with a content of 20 wt. % FL, the surface is characterised by a more homogeneous microstructure, a smaller number of defects and depth of damage. This indicates a decrease in the adhesive component of the friction force and a transition to a predominantly pseudoelastic wear mechanism.

Another factor that contributes to improving the tribological properties of UHMWPE is the ordering of its supramolecular structure, which is due to the reduction of the amount of amorphous phase. This leads to an increase in the degree of crystallinity of the material, improved intermolecular interaction, and a more uniform distribution of the load during friction. From Fig. 3, we can see that the unfilled UHMWPE consists of an orthorhombic phase (*a* = 0.7446 nm, *b* = 0.4980 nm, *c* = 0.2476 nm), (planes (110), (200), (210)) and an amorphous halo.

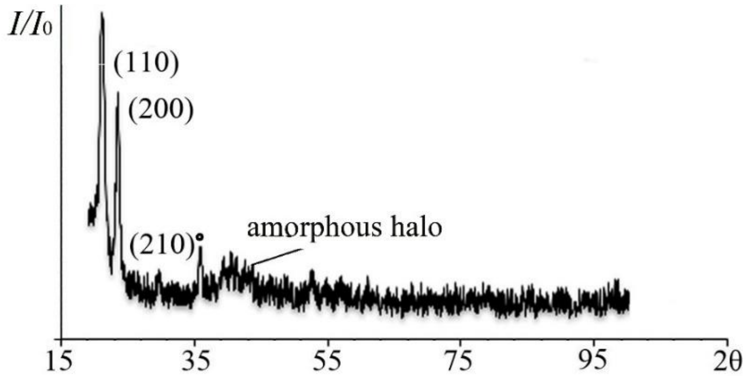

Fig. 3. X-ray diffraction pattern of ultra-high-molecular-weight polyethylene from Jiujiang Zhongke Xinxing New Material Co

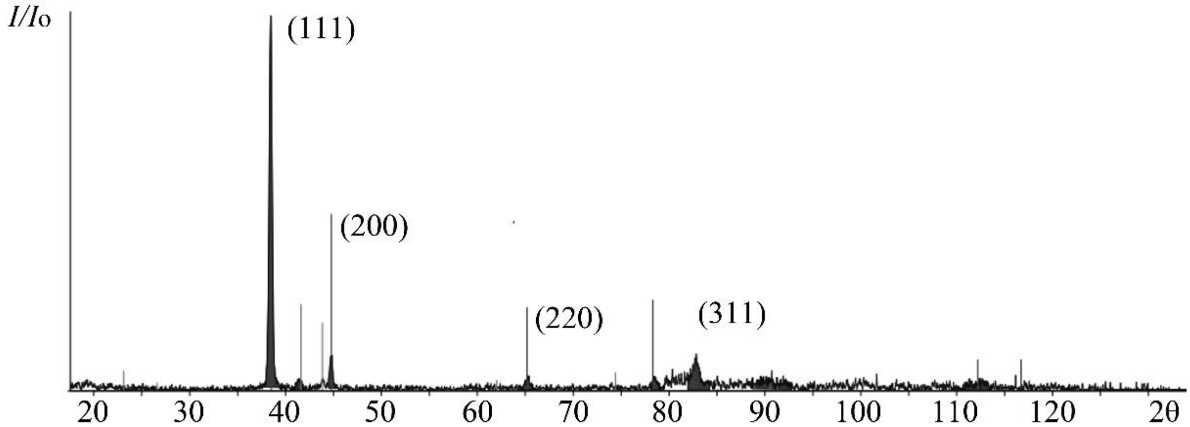

Fig. 4. Diffraction pattern of the binary alloy of the Al-Mn system

The diffraction pattern of the Al-11.6 % Mn alloy (see Fig. 4.) shows that it consists of a mixture of two phases, which are supersaturated aluminium and the Al_6Mn phase. The blued aluminium represents the fcc lattice with a reduced period to 0.4033 nm and a peritectic Al_6Mn phase. The latter forms from the liquid state due to achieving significant supercooling of the melt under QLS conditions. A feature of the diffraction pattern of the Al-Mn ZRS alloy is the redistribution of the intensity of the fcc lattice lines: namely, a significant excess of the intensity of the (111) lines compared to the (200) line, almost 10 times, which is due to the appearance of a texture: the predominant crystallization of the fcc lattice by the (111) plane on the surface of the cooling substrate.

It is worth noting that the most significant improvement in the tribological properties of UHMWPE is observed when introducing 20 wt. % FL. Further increase in its content (25—30 wt. %) leads to a deterioration of the studied indicators due to the formation of local stress concentrators in the polymer matrix. This, in turn, reduces the uniformity and strength of the surface layer, facilitating the development of cracks and grooves during friction. The main reason for this phenomenon is the agglomeration of particles of the binary Al-11.6 % Mn alloy.

The distance between the particles decreases at a high FL content, and intermolecular interactions (particularly Van der Waals forces) begin to prevail, contributing to their adhesion. An increase in the number and size of agglomerates, in turn, reduces the number of active centres of "FL-UHMWPE" interaction, which weakens the effect of microreinforcement.

Conclusions

We established that introducing dispersed particles of the liquid-hardened Al-11.6 % Mn alloy contributes to an increase in the wear resistance of UHMWPE under various operating conditions: under the influence of rigidly fixed abrasive particles and friction conditions without lubrication according to the “disk-pad” scheme. The increase in functional properties is due to the effect of polymer microreinforcement by introducing hard (HV ≈ 600 MPa) alloy particles that strengthen the surface layer. An increase in hardness by 1.7 times compared to pure UHMWPE confirms this. A composite with a binary Al-Mn alloy content of 20 wt. % can be recommended for manufacturing working parts of machines and mechanisms of the agricultural industry, which occurs under conditions of combined adhesive and abrasive wear.

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ВПЛИВ БІНАРНОГО СПЛАВУ СИСТЕМИ AL-MN НА ТРИБОЛОГІЧНІ ВЛАСТИВОСТІ НАДВИСОКОМОЛЕКУЛЯРНОГО ПОЛІЕТИЛЕНУ

Реферат

Комплексний підхід до зменшення адгезійного та абразивного зношування робочих органів сільськогосподарської техніки є важливим чинником підвищення їх довговічності та загальної економічної ефективності аграрного сектору, оскільки майже 90 % випадків передчасного виходу з ладу пов’язані саме з поверхневим руйнуванням. Одним із найбільш перспективних шляхів вирішення цієї проблеми є застосування сучасних полімерних композиційних матеріалів на основі термопластичних полімерів, зокрема надвисокомолекулярного поліетилену, модифікованого порошковими наповнювачами. У статті розглянуто вплив відсоткового вмісту загартованого з рідкого стану дисперсного (50—100 мкм) бінарного сплаву системи Al-Mn на трибологічні властивості надвисокомолекулярного поліетилену в різних умовах експлуатації: при дії жорсткозакріплених абразивних часток та за умов тертя без змащення за схемою «диск-колодка». Встановлено, що введення дисперсних часток твердого сплаву (HV ≈ 600 МПа) дозволяє суттєво зменшити інтенсивність лінійного зношування (у 8,7 разів) та показник абразивного стирання (у 1,8 рази) порівняно з чистим полімером. Підвищення зносостійкості пояснюється ефектом мікропідсилення, що забезпечує рівномірний розподіл прикладеного навантаження у зоні контакту, зниження локальних напружень та зменшення ймовірності утворення мікротріщин. Морфологічний аналіз поверхонь тертя підтвердив формування більш однорідної та стабільної структури поверхневого шару композиту. Водночас показано, що збільшення вмісту сплаву понад 20 мас.% призводить до агломерації часток у полімерній матриці, утворення локальних концентраторів напружень та, як наслідок, до погіршення трибологічних характеристик. Композит із ефективним вмістом бінарного сплаву системи Al-Mn 20 мас.% можна рекомендувати для виготовлення робочих органів машин і механізмів аграрної промисловості, експлуатація яких відбувається в умовах комбінованого адгезійного та абразивного зношування.

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